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Discovery of the first extra-galactic SiO maser*

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Abstract. We report on the detection of SiO J=2–1 v=1 maser emission from the red supergiant IRAS04553–6825 in the LMC. It has thereby become the first known source of SiO maser emission outside the Milky Way.

Key words: Masers — circumstellar matter — Stars: mass loss — supergiants — Magellanic Clouds — Radio lines: stars

1. Introduction

The heaviest post-main sequence mass-loss occurs during the Red Supergiant (RSG, high mass stars) phase or at the tip of the Asymptotic Giant Branch (AGB, intermediate mass stars). In oxygen-rich environments, the velocity structure of the inner part of the circumstellar envelope below the dust formation can be studied in SiO maser emission (Chapman & Cohen 1986). This is where the poorly understood initiation of the mass loss flow occurs.

Recently, the first obscured evolved stars in the LMC were found, using the IRAS database (Reid 1991; Wood et al. 1992; Zijlstra et al. 1995). Wood et al. (1992) discovered OH maser emission from six of these stars: the first known extra-galactic OH/IR stars. We used the SEST at La Silla to observe the best candidates for detection of 86 GHz SiO maser emission among these OH/IR stars. As a first result, we present the discovery of the first extra-galactic SiO maser — viz. the RSG IRAS04553–6825.

2. Observations

The observations were performed on days 25, 30, and 31 of May 1995. We used the 15m SEST (sub)mm telescope at ESO/La Silla with the new 3 mm SIS receiver as the frontend, and the high resolution spectrograph HRS as the backend. We observed the vibrationally excited rotational transition of the silicate molecule SiO(2–1)$_{v=1}$ at 86243.442 MHz. During part of the time we used this configuration simultaneously in combination with the low resolution spectrograph LRS tuned at the same frequency. We observed in a dual beam switch mode with the source alternately placed in the two beams, a method which yields very flat baselines. The beam separation was $\sim 11.5'$. The pointing was checked every few hours, using the nearby bright SiO maser R Dor. This agreed with the specified accuracy of $3''$ rms. The Full Width Half Power of the beam is $57''$. At 86 GHz the channel separation is 0.15 km s^{-1} for the HRS, and 2.4 km s^{-1} for the LRS. The conversion factor from antenna temperature to flux units is 25 Jy K^{-1} at 86 GHz. The internal absolute flux calibration is accurate to about 20%.

Helped by good atmospheric conditions — relative humidity 15 – 30%, and outside air temperature about 15°C with little or no cirrus — the system temperature at 86 GHz was about 120 K or less at elevations above 40°, and about 150 K at an elevation of 20°. Polarization biases were minimized by observing at different hour angles, because the parallactic angle changes with hour angle. Long integrations naturally take care of this.

3. Detection criteria

With the spectrograph having 1600 – 2000 channels — though not all independent of each other — a minimum value for a detection threshold is three times the rms noise level. However, the significance of a resolved spectral feature is higher than its peak intensity suggests.

A better estimate of the significance of a resolved spectral feature is obtained by rebinning the spectrum. By dividing this smoothed spectrum by its rms noise level, the

* based on observations obtained at the European Southern Observatory

peak of the spectral feature is expressed in terms of rms noise level. The peak of the spectral feature will reach the highest significance for one specific binning. This yields the spectral width of the feature and the significance of the integrated spectral feature.

An additional check can be made on a possibly detected maser peak. Since the spectra are averages of many individual scans, statistics can be done on this series of scans. For a specific channel we can calculate the variance over the set of scans, yielding an estimate for the noise level of each channel. A feature in the variance spectrum coincident with a possibly detected maser peak casts doubt on the maser nature of the peak. A maser peak is not expected to vary intrinsically within the course of an observation, which makes an anomaly in the noise more likely. The variance spectrum can also be used to check the derived average rms noise level. In the same way, we can calculate the covariance between one channel and another channel over the set of scans. For each channel, we can integrate this covariance over a fixed number of adjacent channels, obtaining the covariance spectrum. Again, a feature in the covariance spectrum right at the position of the possibly detected maser peak would suggest an anomaly in the noise instead.

We used a few different frequency settings during the course of the observation to check for systematic flux offsets due to bad channels. The distribution of the observations over three separate shifts allows for a check on consistency too. The very unlikely case of an artificial signal in the HRS spectrograph can be ruled out by simultaneous observation with the LRS spectrograph. Finally, proximity in velocity space to an OH detected maser feature further enhances the significance of a possible SiO detection.

4. Results

All HRS spectra of the $SiO(2–1)_{v=1}$ transition of IRAS04553–6825 are added together. The resulting spectrum is shown in Fig. 1 (a and b). This spectrum is the result of a total of 9.9 hours on-source integration time. Due to the beamswitching and overhead from reading/writing, tuning, and pointing checks, the actual observing time was $\sim$ 26 hours. The 1 σ level (= rms) is only 63 mJy. This low a noise level could only be achieved by the excellent performance of the new receiver.

The SiO maser emission is clearly seen as a narrow, yet resolved peak at $v_{hel} \sim 275 - 276$ km s^{-1}, at a level of $\sim 4.6\ \sigma$. We replaced the flux value of each channel by the average flux within a bin, centered on that channel and 15 channels wide (= 2.25 km s^{-1}). The spectrum is shown in Fig. 1 (c). Now, the significance of the maser is 6.9 σ (1 σ = 29 mJy). The maser emission peaks at v_{hel} = 275.6$\pm$0.3 km s^{-1}, with a peak flux $F_{max} = 0.28\pm0.06$ Jy (Fig. 1 (b)). The FWHM of the feature is $\sim$ 1.1 km s^{-1}. The total width of the peak is $\sim$ 2.3 km s^{-1}, with the center-of-gravity at $v_{hel} \sim 275.9$ km s^{-1}. Integrating the feature in the region $v_{hel} = 274.73 - 276.99$ km s^{-1}, we

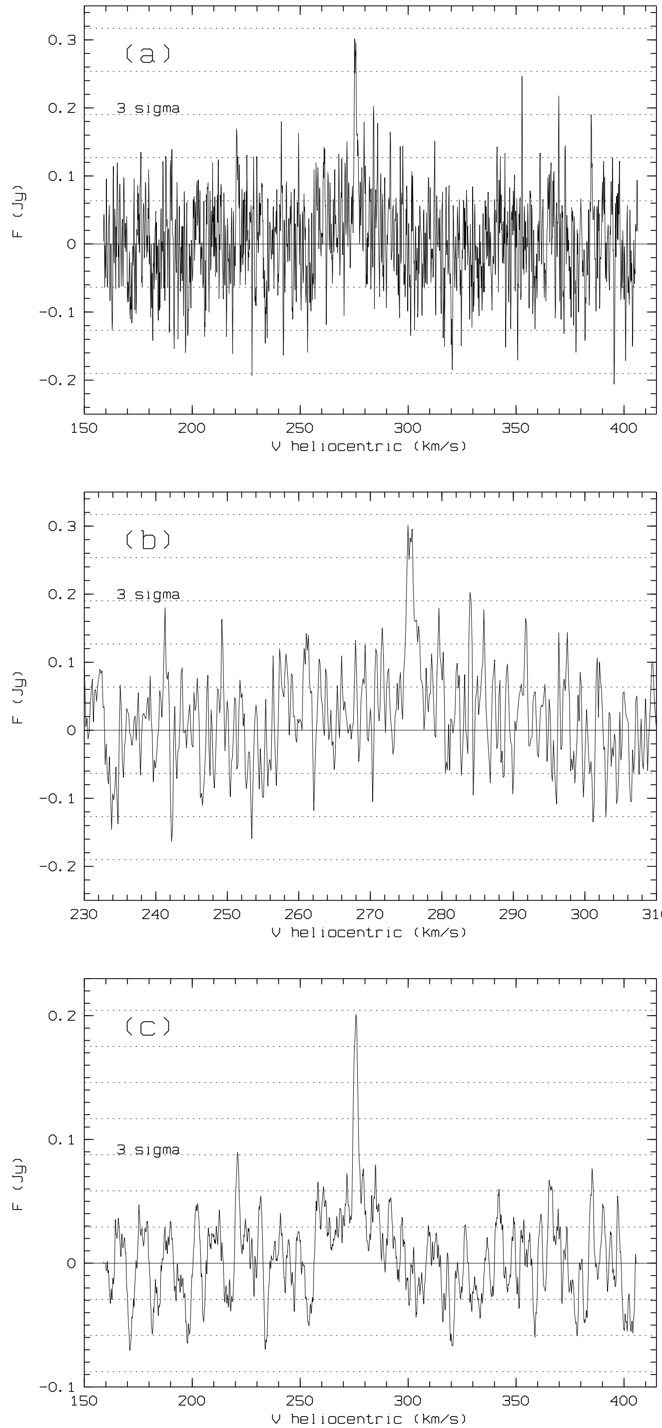

Fig. 1. (a) High resolution (HRS) spectrum around the $SiO(2–1)_{v=1}$ maser emission from IRAS04553–6825. The velocities are heliocentric, and horizontal dotted lines are given per 1 σ (1 σ = 63 mJy). (b) Expanded section of the original HRS spectrum around the maser peak. (c) The HRS spectrum smoothed by averaging over 15 channels (= 2.25 km s^{-1}). Now 1 σ = 29 mJy

obtain an integrated flux $F_{int} = 0.45 \pm 0.07$ Jy km s^{-1}. There is a hint of emission at 260 km s^{-1}, as well as a possible broad pedestal emission component at $v_{hel} \sim 260 - 290$ km s^{-1}. If real, this would imply an integrated flux of about a factor two higher than estimated above.

The variance and covariance spectra were featureless. The peak is also dominantly present in the LRS spectrum that we took during 5.7 hours out of the total on-source integration time. Thus, the maser peak satisfies all the above-mentioned detection criteria.

5. Discussion

The optical counterpart of IRAS04553–6825 is the red supergiant WOH G064 (Westerlund et al. 1981; Elias et al. 1986). It is extremely bright, both bolometric ($M_{bol} \sim -9.3$, Zijlstra et al. 1995) as well as in the mid-IR ($F_{12\mu m} \sim 8$ Jy). The progenitor mass is probably as massive as $\sim 50 M_{\odot}$. For this massive a star, the spectral type is very late: about M7. The severe circumstellar extinction estimated from the (probably self-absorbed) 9.7 μm silicate feature seems to be inconsistent with the relatively moderate circumstellar extinction estimated from the optical. This has usually been taken as an indication for either binarity or a highly flattened circumstellar material distribution (Roche et al. 1993).

SiO maser emission intensity is correlated with the mid-IR luminosity (e.g. Jewell et al. 1991; Lane 1982; Nyman et al. 1993). OH/IR stars which satisfy $K - L < 4$ mag exhibit brighter $SiO(2–1)_{v=1}$ masers than redder stars (Nyman et al. 1993). The SiO maser emission intensity can be highly variable in time, but typically peaks in the first quarter of the pulsation cycle (Lane 1982; Nyman & Olofsson 1986). At the time of the observations IRAS04553–6825 satisfied all of these criteria for being an outstanding candidate for detection of $SiO(2–1)_{v=1}$ maser emission.

IRAS04553–6825 is the first extra-galactic stellar OH maser discovered (Wood et al. 1986) and the strongest stellar 1612 MHz OH maser source in the LMC; it also exhibits 1665 MHz mainline OH maser emission (Wood et al. 1992). Both OH masers are double peaked, from which Wood et al. derived a stellar velocity of $v_\star(OH) \sim 260$ km s^{-1}. The bulk of the presently detected SiO maser emission comes from a peak that is situated redward of the OH maser emission, with a velocity difference with respect to $v_\star(OH)$ of $v_{hel} \sim 16$ km s^{-1}. This is atypical, since SiO maser emission is usually observed to be centered at the stellar velocity (e.g. Heske 1989; Jewell et al. 1991; Lewis et al. 1995; Nyman et al. 1986). SiO maser emission is known to be highly variable in both intensity and line shape in an erratic way on timescales of months (Lane 1982), but excursions of SiO maser peaks only reach several km s^{-1} with respect to the stellar velocity (e.g. Bujarrabal et al. 1986; Lane 1982; Nyman & Olofsson 1986; Olofsson et al. 1985). Thus, it seems likely that the OH is not centred on the stellar velocity. An indication that not all the OH emission has been observed comes from the very low value for the expansion velocity derived from the OH of only 11 km s^{-1}: this is a factor of $3 - 4$ lower than is normally found for supergiants. To confirm this hypothesis, we took a medium resolution spectrum (R $\sim$ 75,000) with the NTT (ESO) in October 1995: the spectrum shows Hα emission peaking at $v_{hel} \sim 274$ km s^{-1} (extending between $v_{hel} \sim 265 - 293$ km s^{-1}), confirming the revised value for the stellar velocity.

The difference between the SiO maser peak velocity and the blue-most edge of the OH emission at $v_{hel} \sim 250$ km s^{-1} yields an expansion velocity of $v_{exp} \sim 26$ km s^{-1}, much more compatible with Milky Way RSGs than the exceptionally low outflow velocity of $v_{exp} \sim 11$ km s^{-1} previously determined. The red-shifted OH emission is not observed. The latter is expected if there is an inner ionized region which is optically thick at 18 cm (e.g. Shepherd et al. 1990). The spectral type of IRAS04553–6825 is not consistent with an ionized stellar wind. The discovery of forbidden [NII] lines (Elias et al. 1986) confirms the existence of ionized gas in its vicinity, but it is not clear whether this HII region is centred on the star.

From the integrated flux of the maser emission, and assuming that the maser emits isotropically, we derive a total photon flux of $\sim 6.8 \times 10^{44}$ photons/s. SiO maser emission is thought to be tangentially amplified (Diamond et al. 1994). For maser emission coming from a rather discrete structure such as a globule, the angle between the maser beam and the line of sight can be non-zero. In that case, the assumption of isotropic emission is no longer valid, which may lead to either over- or under-estimating the total photon flux. Assuming isotropic emission, the observed total photon flux places IRAS04553–6825 at the bright end of the distribution of the Milky Way AGB stars. The total photon fluxes of the RSGs VY CMa and VX Sgr are an order of magnitude larger (Lane 1982), but they are exceptionally bright. Numerical simulations yield larger total photon fluxes with increasing stellar radius (Bujarrabal 1994). Observations showed that the total photon flux also increases with increasing pulsation period (Lane 1982). In this respect, IRAS04553–6825 may not be that similar to Milky Way sources but rather underluminous, since from its very large radius (it is very bright and very cool) and its relatively long period (P $\sim$ 930 d) we might have expected IRAS04553–6825 to be at least as bright as VY CMa and VX Sgr.

Alcolea et al. (1990) found that Mira variables always have a ratio SiO/IR (= $SiO(2–1)_{v=1}$ peak intensity/8 μm intensity) $\sim 1/10$ (see also Hall et al. 1990). This is the maximum pump efficiency and it is only reached in favorable conditions (Bujarrabal et al. 1987). Semi Regular Variables (SRVs)s with visual amplitudes exceeding 2.5 magnitude always have about the maximum efficiency, while SRVs with lower amplitude in V rarely reach the maximum efficiency and are often more than an order of

magnitude less efficient. VY CMa and VX Sgr have ratios SiO/IR $\sim 1/7$ and 1/4, and large amplitudes in V of resp. 3.1 and 7.5 mag. This may be (part of) the cause why these two RSGs exhibit such bright SiO maser emission. IRAS04553–6825 has SiO/IR $\sim 1/30$, which means that it is quite efficient, but not optimal. The small amplitude of 0.3 magnitude in K suggests that IRAS04553–6825 is not a large amplitude variable, although the amplitude in V is unknown. IRAS04553–6825 has an integrated- over peak flux ratio of $F_{int}/F_{max} \sim 2$ km s^{-1}, whereas all detections in Alcolea et al. 1990 have $F_{int}/F_{max} = 2.5 - 6.1$ km s^{-1} (Miras) and $F_{int}/F_{max} \sim 7.0 - 10.7$ km s^{-1} (SRVs). This is another indication that IRAS04553–6825 is probably underluminous in terms of total photon flux.

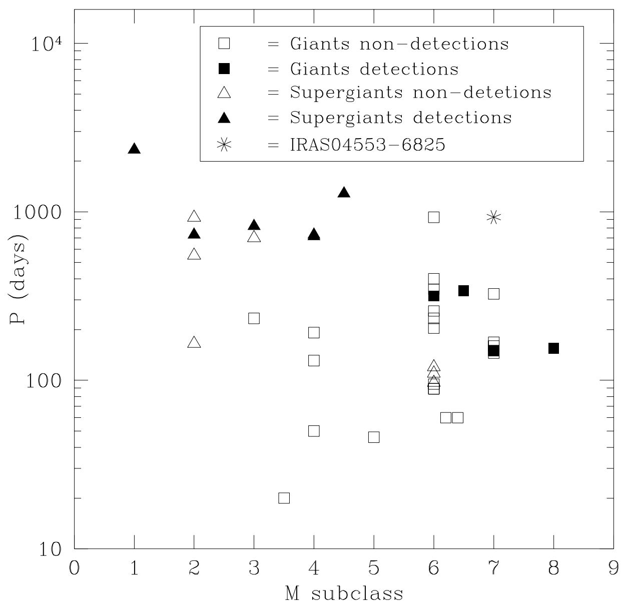

Fig. 2. Periods and spectral types of giants (squares) and RSGs (triangles) from which Alcolea et al. 1990 did (solid symbols) or did not (open symbols) detect SiO(2–1)$_{v=1}$ emission. The star represents IRAS04553–6825

In the sample of Alcolea et al. (1990), all stars with periods exceeding 400 days have spectral types M6 or earlier. The RSGs with detected SiO(2–1)$_{v=1}$ maser emission all have spectral type M4.5 or earlier, whereas detected giants have later spectral types but shorter periods (solid symbols in Fig. 2). The M4.5 RSG NML Cyg (pulsation period P $\sim$ 1280 d) may be the Milky Way star with the closest resemblance to IRAS04553–6825. Alcolea et al. detected SiO(2–1)$_{v=1}$ maser emission from this star with a pump efficiency of only SiO/IR $\sim 1/190$. However, the total photon flux (relative to the 8 μm intensity) is similar to that from IRAS04553–6825. The same is true for their energy distributions (Elias et al. 1986).

6. Conclusions

We discovered the first extra-galactic SiO maser, from the red supergiant IRAS04553–6825 in the LMC. The SiO maser peak was situated 16 km s^{-1} redward of the center of the double peaked OH maser emission. We argue that the SiO maser peak velocity coincides with the stellar velocity. This would mean that the outflow velocity of the circumstellar matter around IRAS04553–6825 is $v_{exp} \sim 26$ km s^{-1}, which is typical for galactic RSGs. The peak intensity of the SiO maser emission is not incompatible with ranges found in galactic RSGs, but the total integrated photon flux is lower than expected.

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